# Chemical Process Utilities

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## Lecture - 11
## Heat Transfer Media and Solar Energy

Welcome to the next part of heat transfer media and solar energy. We will describe the Stirling engine in solar energy, which is most commonly used in various solar cycles. So, previously we had a discussion about the central solar tower. We discussed the solar dish system.

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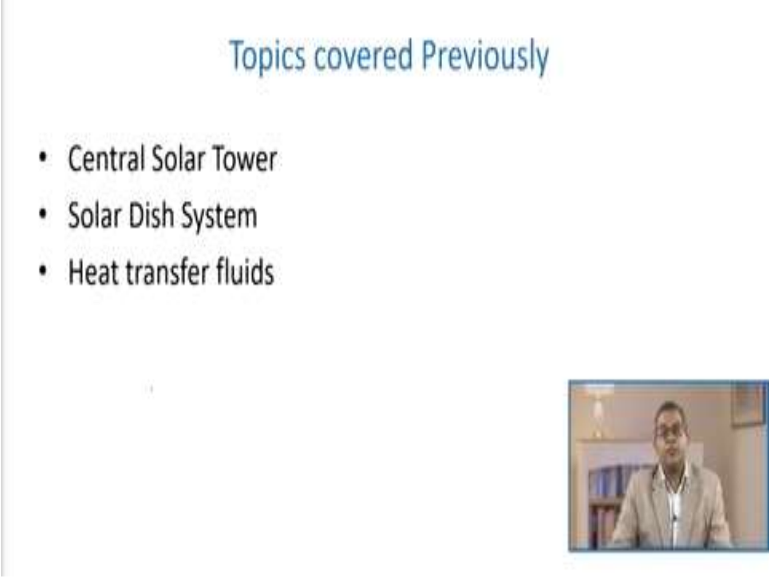

Topics covered Previously

- Central Solar Tower
- Solar Dish System
- Heat transfer fluids

And we were discussing the concept of heat transfer fluid. Apart from this, we discussed the various classification aspects of these heat transfer fluids.

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Topics to be covered

- Heat transfer fluids
  - Water/Steam
  - Thermal Oils
  - Organics
  - Molten Salts
  - Liquid Metals
- Stirling Cycle

In this particular chapter, we will discuss the remaining part of the classification stream of heat transfer fluid that is water or steam, thermal oils, organics, various kinds of organic systems, molten salts, liquid metals, and Stirling cycle used in the solar power cycles.

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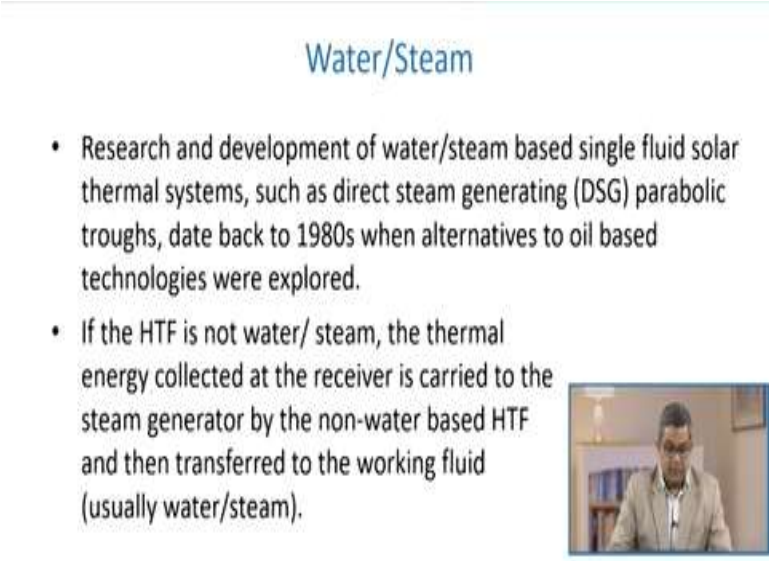

Water/Steam

- Research and development of water/steam based single fluid solar thermal systems, such as direct steam generating (DSG) parabolic troughs, date back to 1980s when alternatives to oil based technologies were explored.
- If the HTF is not water/ steam, the thermal energy collected at the receiver is carried to the steam generator by the non-water based HTF and then transferred to the working fluid (usually water/steam).

So, let us take up the first classification of this particular lecture, and the second one in the series, which is water or steam. Water is again apart from this air it is available in abundance relatively cheaper price and commonly available. So, easily available economic aspects, etcetera it reflects that water is a very good candidate for heat transfer media and it can convert into steam and again, steam is again posed a very good heat transfer media.

So, research and development of water steam system is based on a single fluid solar thermal system like we can produce the direct steam generator DSG parabolic trough, day back in 1980s when alternatives to oil-based technology were explored, and people were trying to go for various kind of non-conventional system then R and D work has been started. If the heat transfer fluid is not water, steam the thermal energy.

Whatever is collected at the receiver is carried to the steam generator by non-water-based heat transfer fluid and then transferred to the working fluid usually, it is the water or steam whatever.

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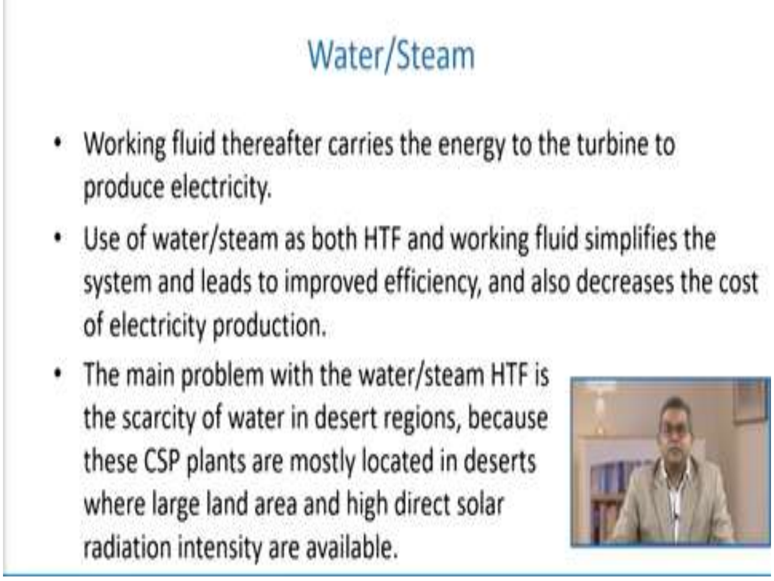

## Water/Steam

- Working fluid thereafter carries the energy to the turbine to produce electricity.
- Use of water/steam as both HTF and working fluid simplifies the system and leads to improved efficiency, and also decreases the cost of electricity production.
- The main problem with the water/steam HTF is the scarcity of water in desert regions, because these CSP plants are mostly located in deserts where large land area and high direct solar radiation intensity are available.

The working fluid thereafter carries this particular amount of energy to the turbine to produce electricity. Use of this water or steam as both heat transfer fluid and a working fluid simplifies the system, leading to improved efficiency and decreasing the cost of electricity production. The main problem with the water steam HTF is the scarcity of water in desert regions.

Because these concentrated solar power plants are mostly located in desert where the large land area, the land area is abundantly available and high direct solar radiation intensity is usually available but there is no water.

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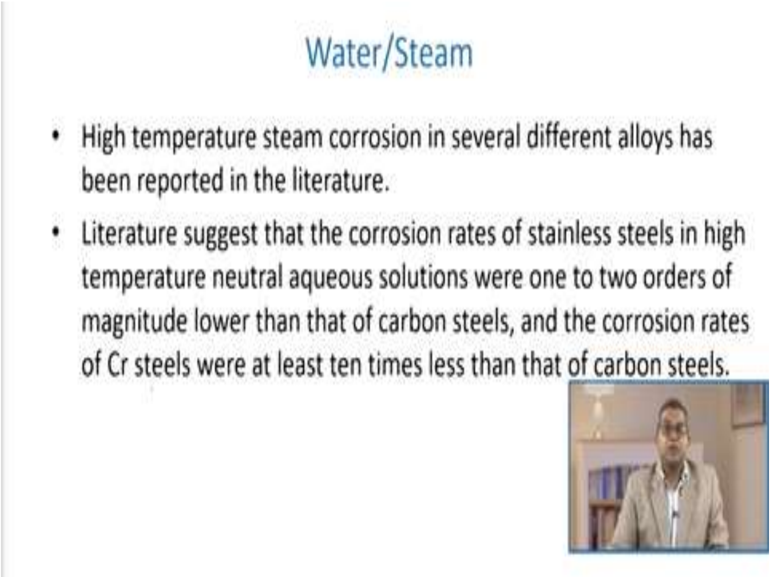

## Water/Steam

- High temperature steam corrosion in several different alloys has been reported in the literature.
- Literature suggest that the corrosion rates of stainless steels in high temperature neutral aqueous solutions were one to two orders of magnitude lower than that of carbon steels, and the corrosion rates of Cr steels were at least ten times less than that of carbon steels.

The high-temperature steam corrosion in several different alloys has been reported in the literature, this is again a very serious problem. So, people have suggested that the corrosion rates of stainless steel in high temperature neutral aqueous solution were one or the two orders of magnitude lower than that of carbon steel. The corrosion rate of chromium steel that were at least 10 times less than that of the carbon steel.

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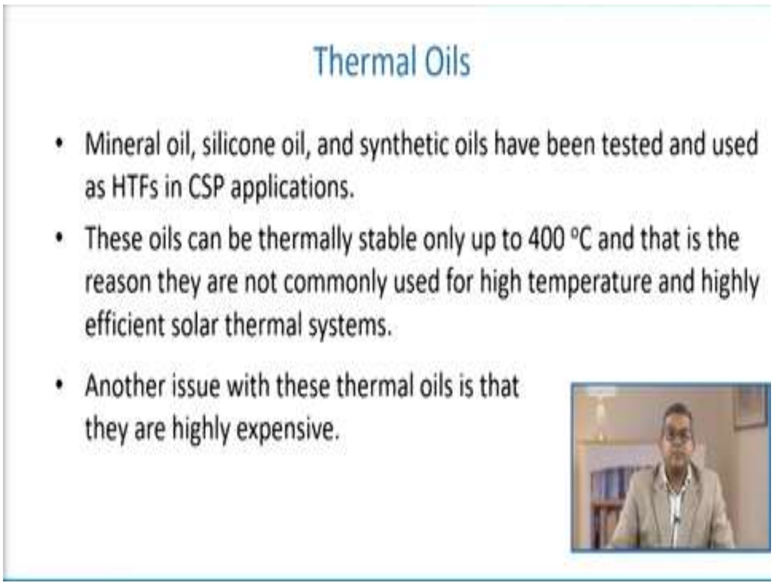

## Thermal Oils

- Mineral oil, silicone oil, and synthetic oils have been tested and used as HTFs in CSP applications.
- These oils can be thermally stable only up to 400 °C and that is the reason they are not commonly used for high temperature and highly efficient solar thermal systems.
- Another issue with these thermal oils is that they are highly expensive.

So, people have used the water, and still, the water is being used as a heat transfer media very commonly, and the best example is your boiler where you are producing the steam, discharging that steam to give the latent heat and then you are condensing the water and again recirculating it. So, it offers the wide spectrum but the only limitation with the water is that it has some pressure-sensitive or temperature-sensitive approaches.

So, you cannot go beyond and specific levels. So, in that case, suppose that if you wish to produce the steam at, say, 300 degrees Celsius, then the pressure limitation may come into the picture. In that case, you are always looking for some cost-effective heat transfer fluid. And obviously, you are looking for some more ranges of heat transfer fluid with respect to the temperature thermal oils.

These are offering again a long-range of temperature spectrum, and these thermal oils are attributed to mineral oil, silicone oil, and synthetic oils. So,  have been tested used as the heat transfer fluid in various concentrated solar power applications. These oils can be thermally stable only say up to 400 degree Celsius because beyond this may have the tendency to dissociate disintegrate.

Conclusion and may cause some environmental problems and may create the corrosion issues and safety-related issues in the system in question. Moreover, that is the reason they are commonly used for high temperature and highly efficient solar thermal systems because they can use up to say 400 degrees Celsius. Another issue with this thermal oil is that are very expensive mineral oil, silicone oil, and synthetic these oils are very much expensive because of the processing cost.

Then people have used several organics material used as heat transfer fluids in the concentrated solar power system.

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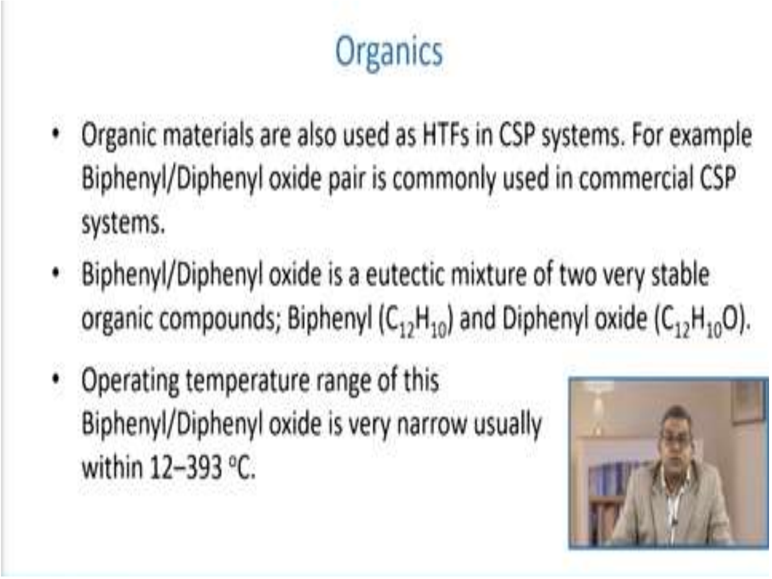

Organics

- Organic materials are also used as HTFs in CSP systems. For example Biphenyl/Diphenyl oxide pair is commonly used in commercial CSP systems.
- Biphenyl/Diphenyl oxide is a eutectic mixture of two very stable organic compounds; Biphenyl ($C_{12}H_{10}$) and Diphenyl oxide ($C_{12}H_{10}O$).
- Operating temperature range of this Biphenyl/Diphenyl oxide is very narrow usually within 12–393 °C.

For example, biphenyl and diphenyl oxide are commonly used in commercial concentrated solar power systems. This Biphenyl Diphenyl oxide is a eutectic mixture of two very stable organic compounds that is Biphenyl referred as C 12 H 10 and Diphenyl oxide referred as C 12 H 10 O. you see the operating temperature range because obviously, as an engineering perspective, we are looking for the operating temperature range.

So, the operating temperature range of this biphenyl diphenyl oxide is very narrow, usually within 12 to 393 degrees Celsius.

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Organics

- The first solar thermal plant with this organic material as the HTF was commissioned in 2009 at Badajoz, Spain and currently there are a total of eight solar thermal plants operating with Biphenyl/Diphenyl oxide.
- Another similar plant named as Megha Solar Plant CSP Project, a concentrating solar power (CSP) project, located at Anantapur, Andhra Pradesh, is started on year 2014 with production capacity of 50 MW electricity.

The first solar thermal power plant with these organic materials as the heat transfer fluid was commissioned in 2009 at Badajoz, Spain and currently there are a total of eight solar thermal power plants operating with Biphenyl Diphenyl oxide. Another similar type of plant named Megha Solar plant CSP project, a concentrating solar power project located at Anantapur, Andhra Pradesh in India, started in year 2014 with a production capacity of 50-megawatt electricity.

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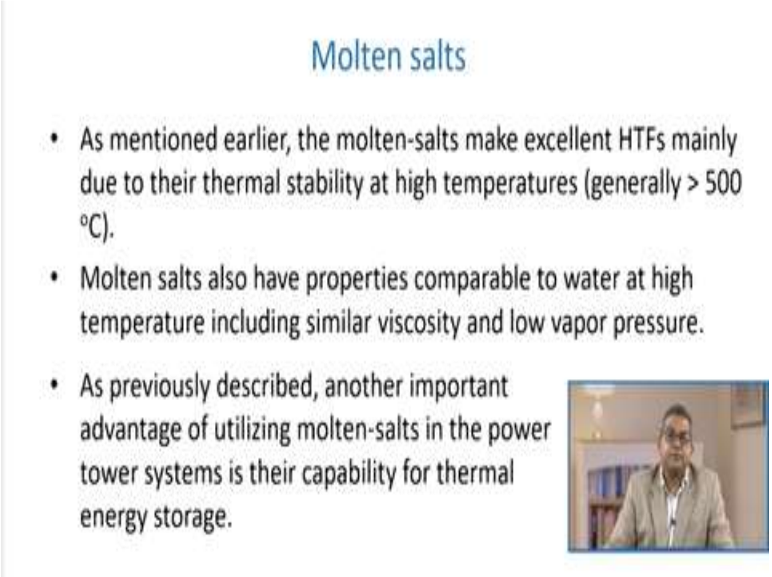

## Molten salts

- As mentioned earlier, the molten-salts make excellent HTFs mainly due to their thermal stability at high temperatures (generally > 500 °C).
- Molten salts also have properties comparable to water at high temperature including similar viscosity and low vapor pressure.
- As previously described, another important advantage of utilizing molten-salts in the power tower systems is their capability for thermal energy storage.

Apart from this, there are certain molten salts, and these organic materials are again having a large spectrum of temperature range operating temperature range. So, these molten salts make excellent heat transfer fluids mainly due to their thermal stability at high temperatures and generally greater than 500 degrees Celsius. Molten salts also have properties comparable to water at high temperatures, including similar viscosity and low vapor pressure.

Another important advantage of utilizing molten salt in the power tower system is thermal energy storage capability. Again, this is quite important how much thermal energy it can be stored because subsequently, it can be utilized in the process.

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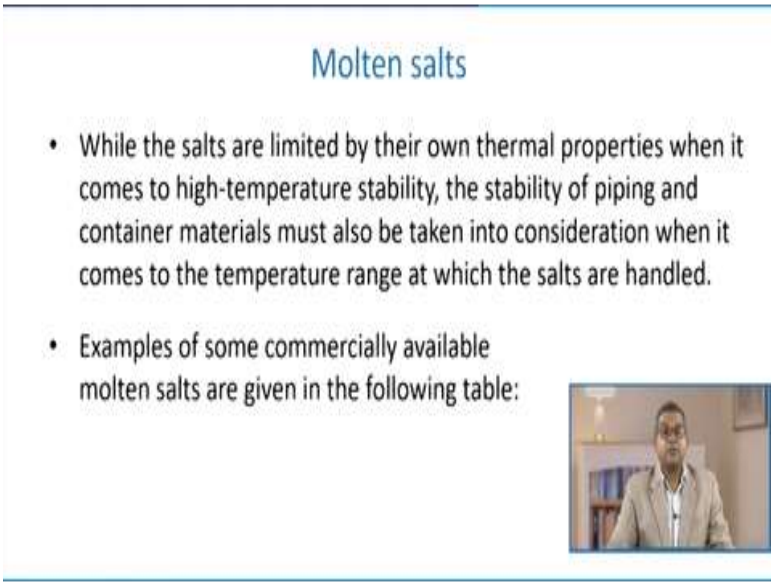

## Molten salts

- While the salts are limited by their own thermal properties when it comes to high-temperature stability, the stability of piping and container materials must also be taken into consideration when it comes to the temperature range at which the salts are handled.
- Examples of some commercially available molten salts are given in the following table:

So, while the salts are limited by their own thermal properties when it comes to high-temperature stability, the stability of piping and container material must also be taken into consideration when it comes to the temperature range at which these salts are handled.

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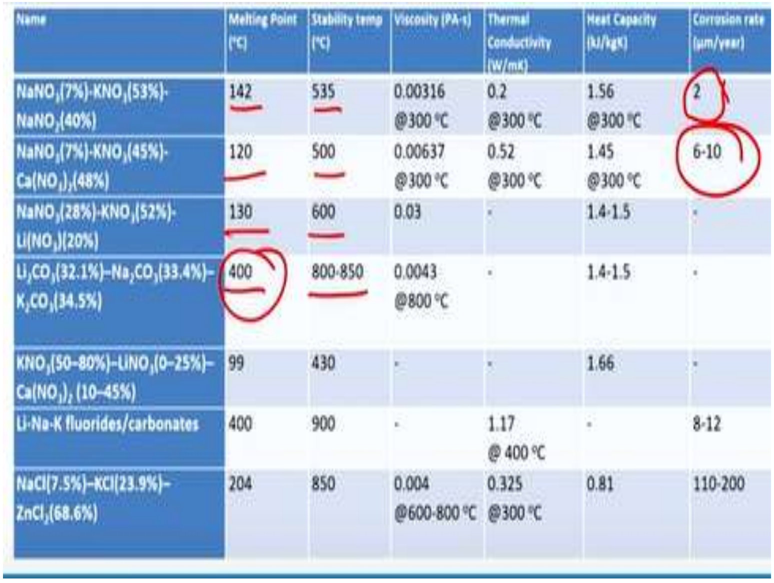

| Name | Melting Point (°C) | Stability temp (°C) | Viscosity (PA-s) | Thermal Conductivity (W/mK) | Heat Capacity (kJ/kgK) | Corrosion rate (μm/year) |
|---|---|---|---|---|---|---|
| $NaNO_3(7\%)-KNO_3(53\%)-NaNO_2(40\%)$ | 142 | 535 | 0.00316 @300 °C | 0.2 @300 °C | 1.56 @300 °C | 2 |
| $NaNO_3(7\%)-KNO_3(45\%)-Ca(NO_3)_2(48\%)$ | 120 | 500 | 0.00637 @300 °C | 0.52 @300 °C | 1.45 @300 °C | 6-10 |
| $NaNO_3(28\%)-KNO_3(52\%)-Li(NO_3)(20\%)$ | 130 | 600 | 0.03 | - | 1.4-1.5 | - |
| $Li_2CO_3(32.1\%)–Na_2CO_3(33.4\%)–K_2CO_3(34.5\%)$ | 400 | 800-850 | 0.0043 @800 °C | - | 1.4-1.5 | - |
| $KNO_3(50–80\%)–LiNO_3(0–25\%)–Ca(NO_3)_2\ (10–45\%)$ | 99 | 430 | - | - | 1.66 | - |
| Li-Na-K fluorides/carbonates | 400 | 900 | - | 1.17 @ 400 °C | - | 8-12 |
| $NaCl(7.5\%)–KCl(23.9\%)–ZnCl_2(68.6\%)$ | 204 | 850 | 0.004 @600-800 °C | 0.325 @300 °C | 0.81 | 110-200 |

We have enlisted some of the commercially available molten salts with their various parameters in this table: NaNO3, KNO3, NaNO3 salt. The melting point is 142 degree Celsius with a stability temperature of 535 and viscosity, thermal conductivity and the heat capacity is given. the apart from this the corrosion rate is again very important because obviously it is quite desirable that it should not be corrosive in nature.

Similarly, NaNO3 that is the blend of this salt the NaNO3, 7% KNO3, 45%, and CaNO3 hold twice 48%. It possesses the melting point is 120 degrees Celsius, a stability temperature of 500 and corrosion rate of 6 to 10. Similarly, sodium nitrate, potassium nitrate, and lithium nitrate are having a melting point of say 130 degrees Celsius with a stability temperature 600 degree Celsius.

Then we have enlisted a couple of more salts, and these salts like Li 2 CO 3 Na 2 CO 3 and potassium carbonate are having the 400 degree Celsius melting point with a stability temperature of 800 to 850 degree Celsius. So, we have enlisted all these things and these all parameters like melting point, stability temperature, viscosity, thermal conductivity, heat capacity, corrosion rates all these things are extremely important while selection of while we are selecting the proper salt for our operation in question.

Another category of this heat transfer fluid is liquid metal. This liquid metal has been used in various nuclear industries since 1940 and are currently being studied for use in the solar thermal system as heat transfer fluid and thermal storage media.

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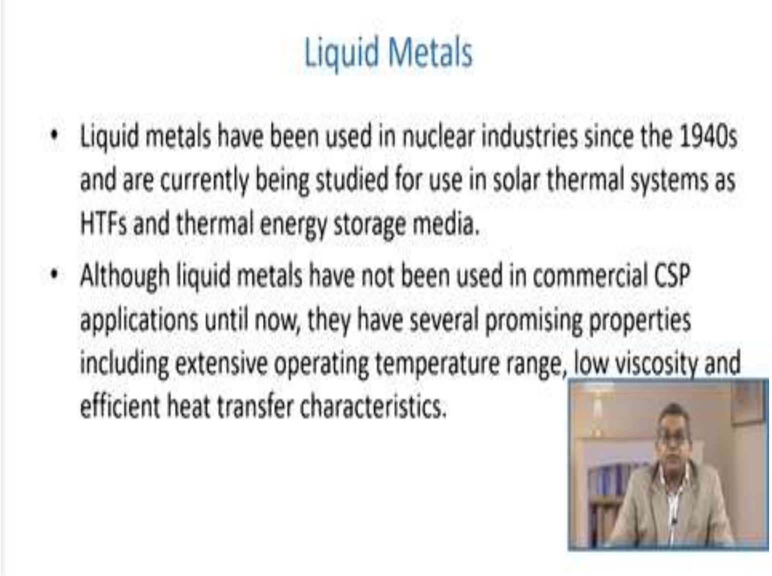

Liquid Metals

- Liquid metals have been used in nuclear industries since the 1940s and are currently being studied for use in solar thermal systems as HTFs and thermal energy storage media.
- Although liquid metals have not been used in commercial CSP applications until now, they have several promising properties including extensive operating temperature range, low viscosity and efficient heat transfer characteristics.

These liquid metals have not been used in commercial concentrated solar power application until now. However, several promising properties have extensive operating temperature range, low viscosity, and efficient heat transfer characteristics.

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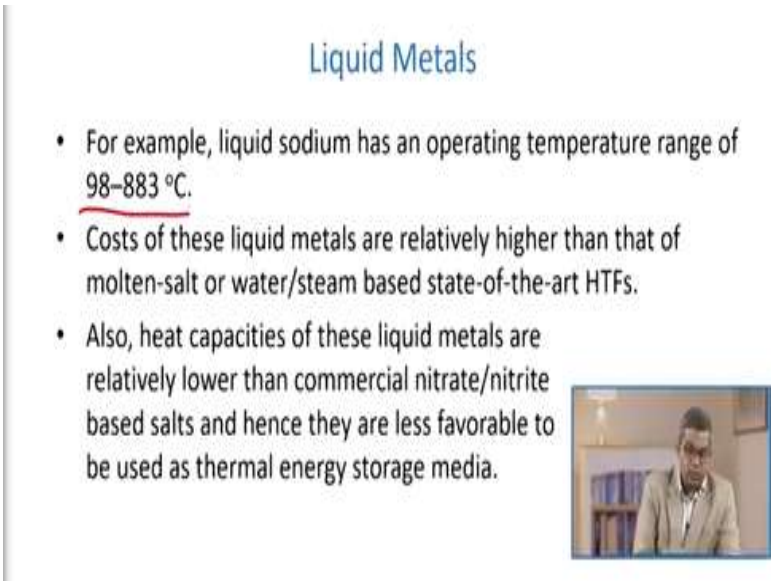

Liquid Metals

- For example, liquid sodium has an operating temperature range of 98–883 °C.
- Costs of these liquid metals are relatively higher than that of molten-salt or water/steam based state-of-the-art HTFs.
- Also, heat capacities of these liquid metals are relatively lower than commercial nitrate/nitrite based salts and hence they are less favorable to be used as thermal energy storage media.

For example, liquid sodium has an operating temperature range from 98 to 883 degrees Celsius. one major disadvantage of this liquid metal is the cost. The cost of these liquid metals is relatively higher than that of molten salt or steam water system. Also heat capacities of these liquid metals are relatively lower than various commercially available nitrates, nitrite-based salt.

And therefore, they are less favorable to be used as a thermal storage media thermal energy storage media. Let us take the example of liquid sodium. This was first used as a heat transfer fluid and storage media in 1981 in a test plant located in Almeria, Spain.

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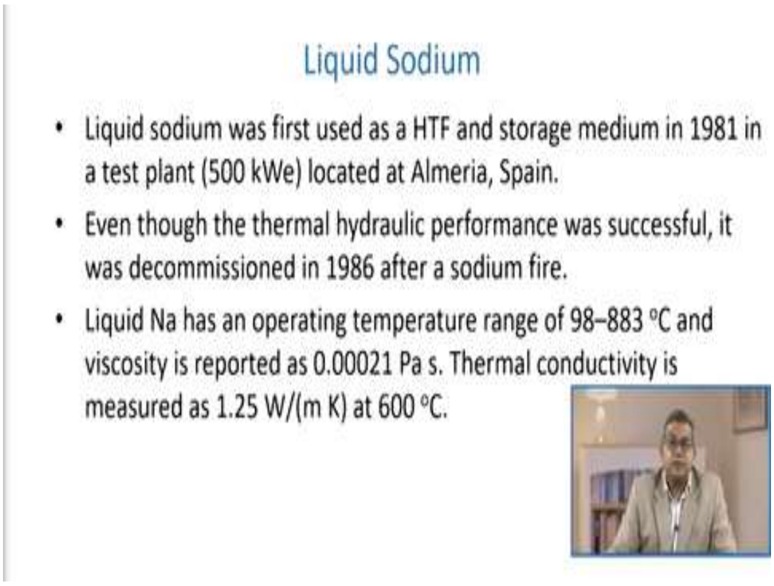

Liquid Sodium

- Liquid sodium was first used as a HTF and storage medium in 1981 in a test plant (500 kWe) located at Almeria, Spain.
- Even though the thermal hydraulic performance was successful, it was decommissioned in 1986 after a sodium fire.
- Liquid Na has an operating temperature range of 98–883 °C and viscosity is reported as 0.00021 Pa s. Thermal conductivity is measured as 1.25 W/(m K) at 600 °C.

Even though the thermal hydraulic performance was successful, it was decommissioned in 1986 after a sodium fire because sodium is very sensitive and very much hygroscopic in nature. So, liquid sodium has an operating temperature range of as we discussed earlier that 98 to 883 degree Celsius and viscosity is reported to 0.00021 Pascal second. The thermal conductivity is 1.25 watt per meter kelvin at 600 degrees Celsius.

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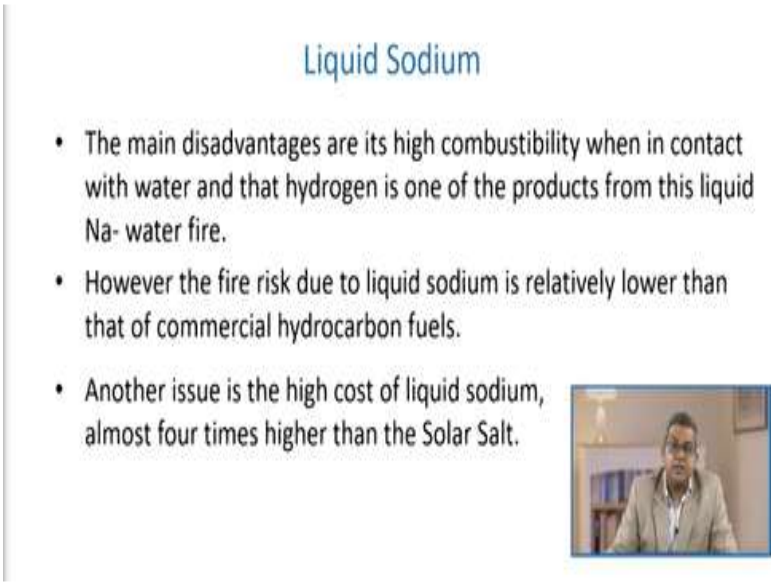

## Liquid Sodium

- The main disadvantages are its high combustibility when in contact with water and that hydrogen is one of the products from this liquid Na- water fire.
- However the fire risk due to liquid sodium is relatively lower than that of commercial hydrocarbon fuels.
- Another issue is the high cost of liquid sodium, almost four times higher than the Solar Salt.

The main disadvantage or you can say the disadvantages are its high combustibility when in contact with water and that hydrogen is one of the products of this liquid sodium water fire. So, I mean, hydrogen is extremely dangerous when the question of fire came into existence. However, the fire risk due to the liquid sodium is relatively lower than that of commercial hydrocarbon fuels.

Another issue is that the high cost of liquid sodium is almost four times higher than solar salt. As far as corrosion issues are in question, generally liquid sodium is less aggressive than the other liquid metals with stainless steel.

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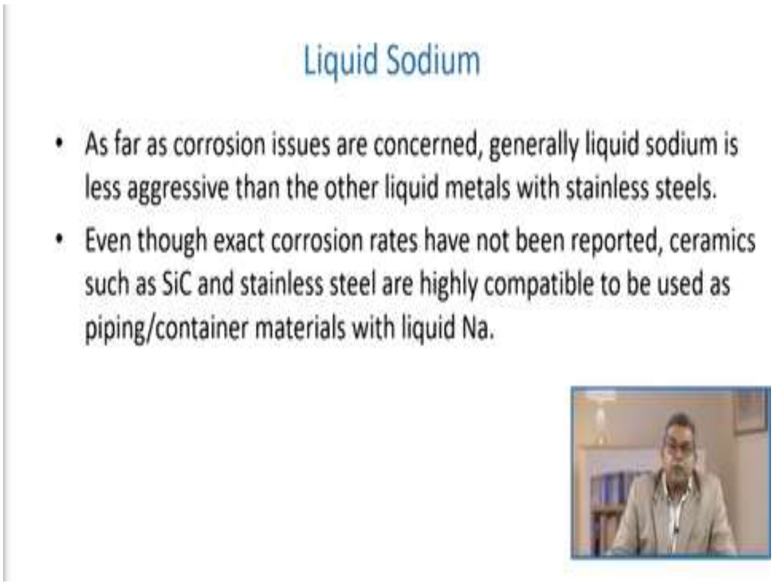

## Liquid Sodium

- As far as corrosion issues are concerned, generally liquid sodium is less aggressive than the other liquid metals with stainless steels.
- Even though exact corrosion rates have not been reported, ceramics such as SiC and stainless steel are highly compatible to be used as piping/container materials with liquid Na.

Even though the exact corrosion rates have not been reported the ceramics such as SiC and stainless steel are highly compatible to be used as piping container material with liquid sodium.

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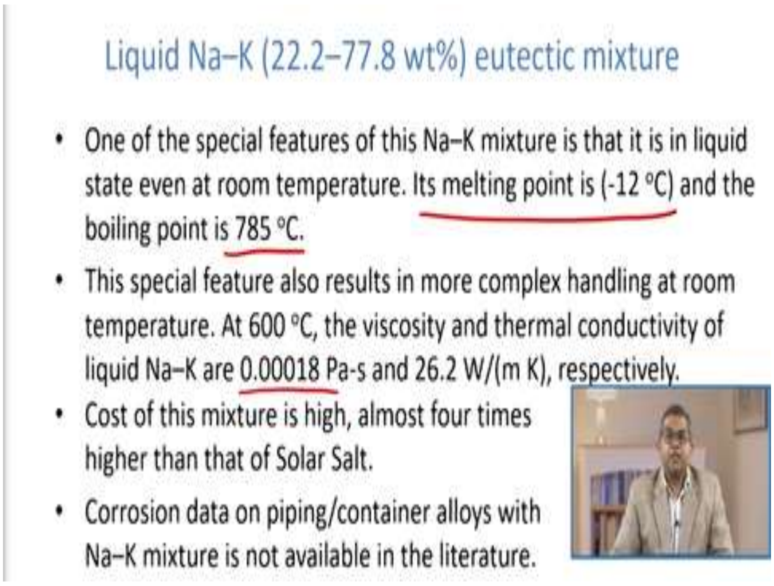

Liquid Na–K (22.2–77.8 wt%) eutectic mixture

- One of the special features of this Na–K mixture is that it is in liquid state even at room temperature. Its melting point is (-12 °C) and the boiling point is 785 °C.
- This special feature also results in more complex handling at room temperature. At 600 °C, the viscosity and thermal conductivity of liquid Na–K are 0.00018 Pa-s and 26.2 W/(m K), respectively.
- Cost of this mixture is high, almost four times higher than that of Solar Salt.
- Corrosion data on piping/container alloys with Na–K mixture is not available in the literature.

Liquid sodium- potassium 22.2 to 77.8 weight % eutectic mixture, one of the special features of this sodium potassium mixture is in liquid state even at room temperature. Its melting point is minus 12 degree Celsius and the boiling point is 785 degree Celsius. This special feature also results in more complex handling. At room temperature, at 600 degree Celsius the viscosity and thermal conductivity of this liquid sodium-potassium it is at 0.00018 Pascal second and 26.2 watt per meter kelvin, respectively.

The cost of this mixture is high almost four times higher than that of the solar salt as far as the corrosion data on the piping container alloy with this particular mixture is as on date it is not available in the literature.

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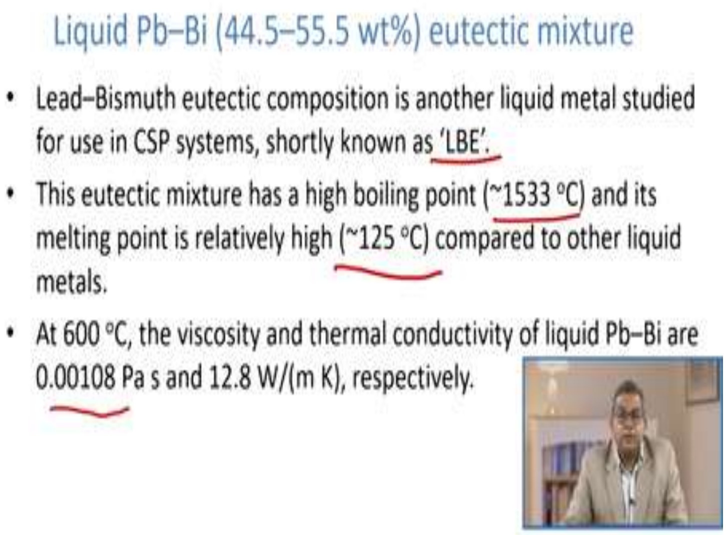

Liquid Pb–Bi (44.5–55.5 wt%) eutectic mixture

- Lead–Bismuth eutectic composition is another liquid metal studied for use in CSP systems, shortly known as 'LBE'.
- This eutectic mixture has a high boiling point (~1533 °C) and its melting point is relatively high (~125 °C) compared to other liquid metals.
- At 600 °C, the viscosity and thermal conductivity of liquid Pb–Bi are 0.00108 Pa s and 12.8 W/(m K), respectively.

Lead-Bismuth eutectic mixture that is 44.5 to 55.5 weight percent this lead bismuth eutectic mixed composition is another liquid metal which is studied for the concentrated solar power system and shortly it is known as LBE. This eutectic mixture has a high boiling point you see that it is around 1533 degrees Celsius and its melting point is relatively high, and that is around 125 degrees Celsius compared to other liquid metals.

At 600 degrees Celsius, liquid lead bismuth's viscosity and thermal conductivity are at 0.00108 Pascal second and 12.8 watts per meter kelvin, respectively.

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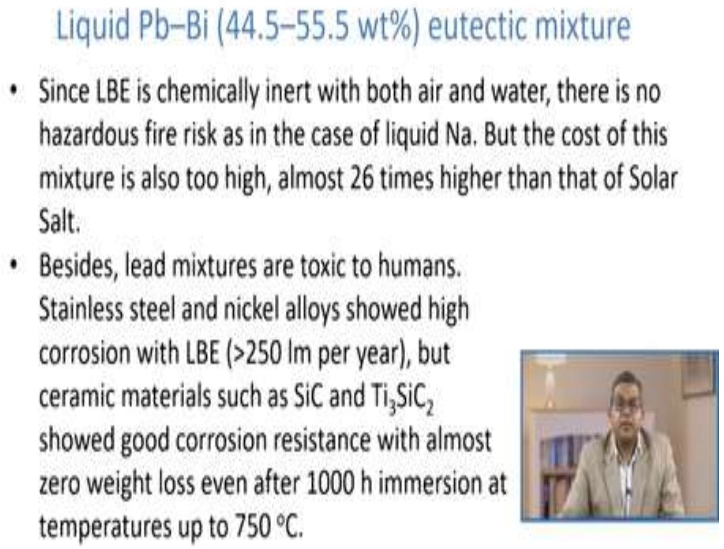

### Liquid Pb–Bi (44.5–55.5 wt%) eutectic mixture

- Since LBE is chemically inert with both air and water, there is no hazardous fire risk as in the case of liquid Na. But the cost of this mixture is also too high, almost 26 times higher than that of Solar Salt.
- Besides, lead mixtures are toxic to humans. Stainless steel and nickel alloys showed high corrosion with LBE (>250 lm per year), but ceramic materials such as SiC and Ti$_3$SiC$_2$ showed good corrosion resistance with almost zero weight loss even after 1000 h immersion at temperatures up to 750 °C.

Since liquid Bismuth eutectic mixture is chemically inert with both air and water, there is no hazardous fire risk as in the case of liquid sodium, which we observed. But the cost of this mixture is again extremely high it is almost 26 times higher than that of the solar salt. Besides this lead mixtures are toxic in nature, especially to human beings. Stainless steel and nickel alloy showed high corrosion with LBE that is greater than 250 per meter per year.

But ceramic materials such as SiC and Ti 3 SiC 2 showed good corrosion resistance with almost zero weight lost even after 1000 hour of immersion at the temperature up to 750 degrees Celsius.

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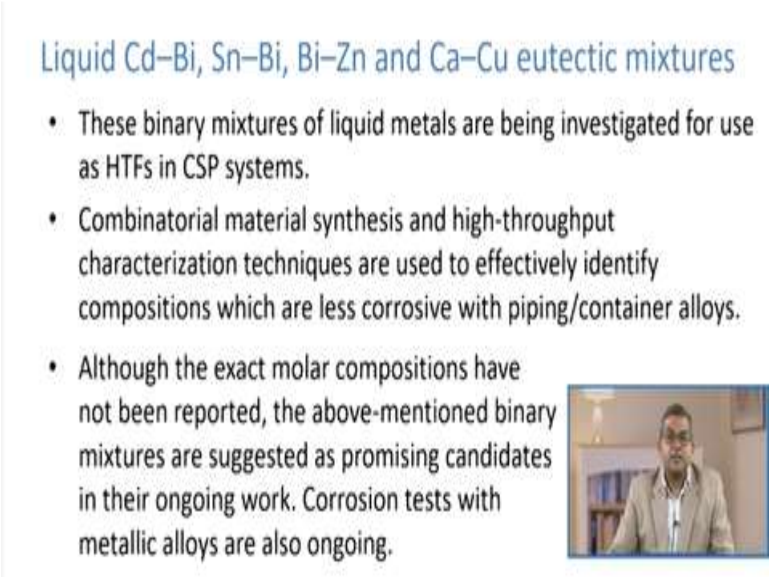

## Liquid Cd–Bi, Sn–Bi, Bi–Zn and Ca–Cu eutectic mixtures

- These binary mixtures of liquid metals are being investigated for use as HTFs in CSP systems.
- Combinatorial material synthesis and high-throughput characterization techniques are used to effectively identify compositions which are less corrosive with piping/container alloys.
- Although the exact molar compositions have not been reported, the above-mentioned binary mixtures are suggested as promising candidates in their ongoing work. Corrosion tests with metallic alloys are also ongoing.

There are many other mixtures available like Cadmium bismuth, Tin bismuth, bismuth zinc, and calcium copper eutectic mixture. These binary mixtures of liquid metals are being investigated for use in heat transfer fluid in concentrated solar power system. Combinational material synthesis and high throughput characterization techniques are used to effectively identify the less corrosive composition with the piping system or container system.

Although the exact molar compositions have not been reported. These binary mixtures are suggested as promising candidates in their ongoing work. Corrosion tests with the metallic alloy are also going on.

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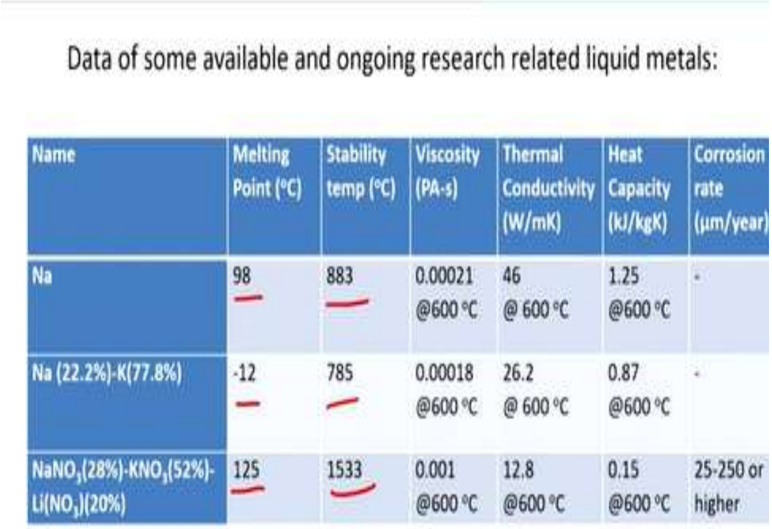

Data of some available and ongoing research related liquid metals:

| Name | Melting Point (°C) | Stability temp (°C) | Viscosity (PA-s) | Thermal Conductivity (W/mK) | Heat Capacity (kJ/kgK) | Corrosion rate (µm/year) |
|---|---|---|---|---|---|---|
| Na | 98 | 883 | 0.00021 @600 °C | 46 @ 600 °C | 1.25 @600 °C | - |
| Na (22.2%)-K(77.8%) | -12 | 785 | 0.00018 @600 °C | 26.2 @ 600 °C | 0.87 @600 °C | - |
| $NaNO_3$(28%)-$KNO_3$(52%)-$Li(NO_3)$(20%) | 125 | 1533 | 0.001 @600 °C | 12.8 @600 °C | 0.15 @600 °C | 25-250 or higher |

We have listed data pertaining to the available and ongoing research related to liquid metals like sodium, sodium potassium, sodium nitrate, potassium nitrate, and lithium nitrate with a melting point stability, viscosity, thermal conductivity, and heat capacity corrosion rate. So, as we said, you see that here the range is 98 to 883, minus 12 to 785 you can say the temperature range is 797, 125 to 1533.

So, as far as this range is in question this is again a very promising one but apart from this the corrosion effect, the availability, the cost all these factors which we need to address. Let us take the Stirling cycle. We had already discussed this stirling cycle in the solar energy system and in parabolic disk system, we have seen that a heat engine is required based on the stirling cycle.

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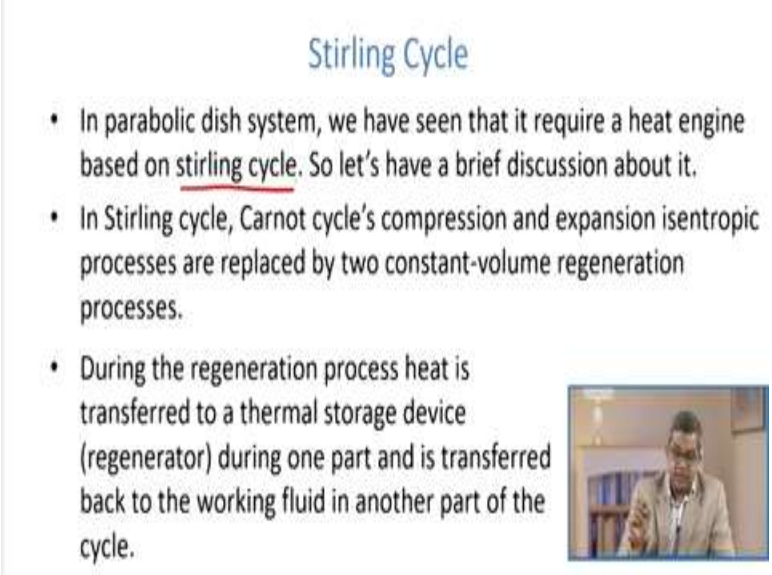

Stirling Cycle

- In parabolic dish system, we have seen that it require a heat engine based on stirling cycle. So let's have a brief discussion about it.
- In Stirling cycle, Carnot cycle's compression and expansion isentropic processes are replaced by two constant-volume regeneration processes.
- During the regeneration process heat is transferred to a thermal storage device (regenerator) during one part and is transferred back to the working fluid in another part of the cycle.

So, let us have a brief discussion about it. In a Stirling cycle, the Carnot cycles compression and isentropic expansion process are replaced by two constant-volume regeneration processes. During the regeneration process, heat is transferred to a thermal storage device that is called the regenerator during one part, and it is transferred back to the working fluid in another part of the cycle.

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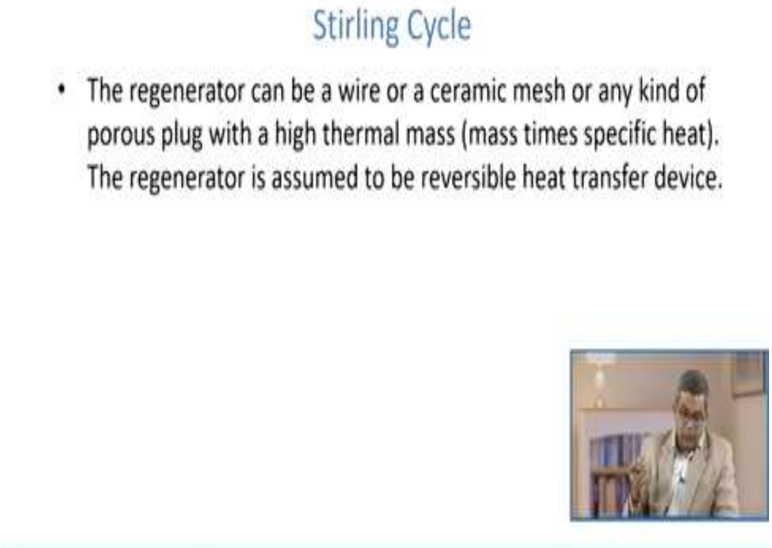

## Stirling Cycle

- The regenerator can be a wire or a ceramic mesh or any kind of porous plug with a high thermal mass (mass times specific heat). The regenerator is assumed to be reversible heat transfer device.

The regenerator can be a wire or ceramic mesh or any kind of a porous plug with high thermal mass. The regenerator is assumed to be a reversible heat transfer device.

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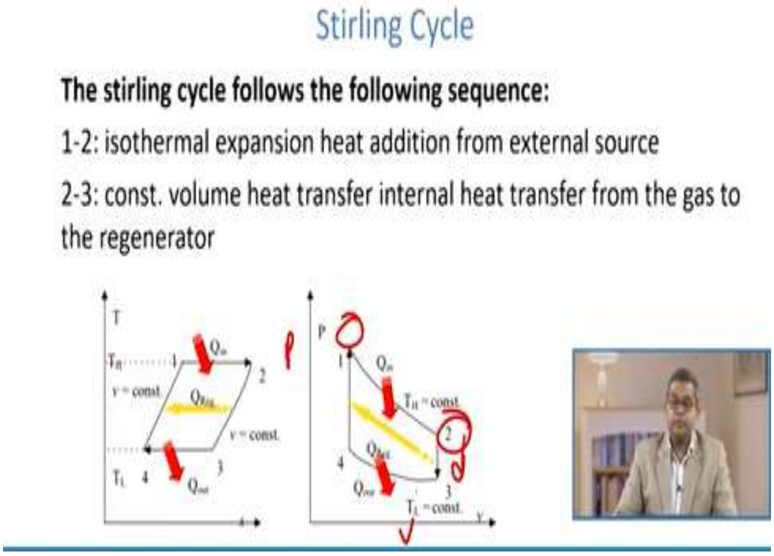

## Stirling Cycle

**The stirling cycle follows the following sequence:**

1-2: isothermal expansion heat addition from external source

2-3: const. volume heat transfer internal heat transfer from the gas to the regenerator

The stirling cycle because as we see in the Rankine cycle or Carnot cycle, are having the several sequences or several steps. here you see that this in this diagram here you see that from stage 1 to stage 2. This is thermal expansion heat addition from the some of the external source. And from station 2 to station 3 there is a constant volume this in this PV diagram this is a concept constant volume heat transfer, internal heat transfer from the gas to the regenerator.

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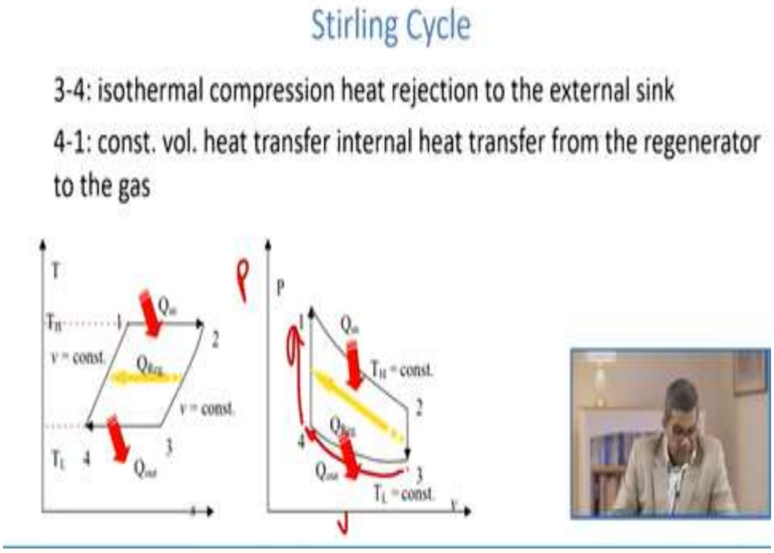

Stirling Cycle

3-4: isothermal compression heat rejection to the external sink

4-1: const. vol. heat transfer internal heat transfer from the regenerator to the gas

Again if we go through from 3 to 4, this is the isothermal compression heat rejection to the external sink. And again, it goes back to from 4 to 1 which is the constant volume heat transfer internal heat transfer from the regenerator to the gas. if you try to replicate this particular step in this TS diagram you can see a similar type of observation as we discussed in the Carnot cycle.

**(Video Starts: 23:15)**

here this small animation reflects the sterling cycle Robert Stirling invented this in 1816. The execution of a stirling cycle requires innovative hardware, which is why the stirling cycle is not in common in practice. it is quite simple that you are supplying the heat source from here this the inner gas inside the cylinder-piston assembly tends to increase by this way it is pushing the system to the back of the system.

Here this is the condenser system where it absorbs the heat and the gas is again then cooled down. So, by this way you are producing the mechanical power over here.

**(Video Ends: 24:04)**

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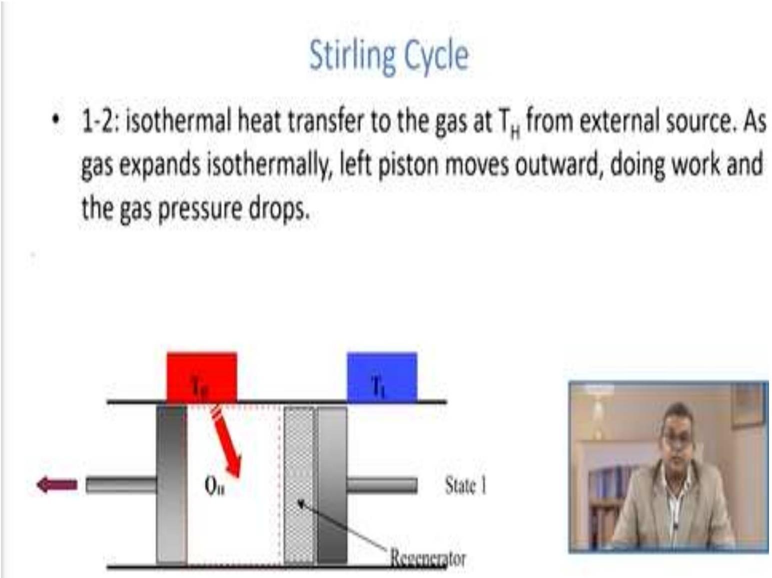

Stirling Cycle

- 1-2: isothermal heat transfer to the gas at $T_H$ from external source. As gas expands isothermally, left piston moves outward, doing work and the gas pressure drops.

When we talk about this sterling cycle, the stage 1 to 2 in the previous system, this is the isothermal heat transfer to the gas maintained at T H from external sources.

**(Video Starts: 24:22)**

So, as we see that gas expands isothermally, it is expense isothermally. This left system moves outward, so it is moving outward during the work and the gas pressure drops.

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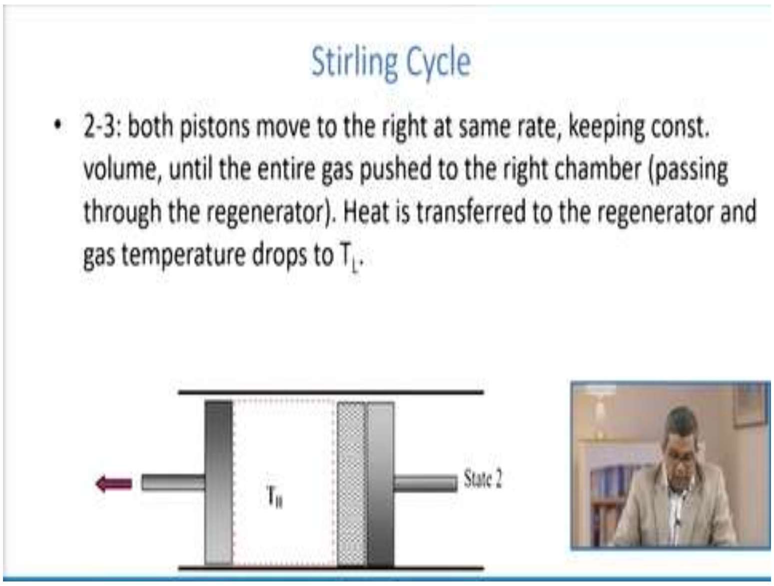

Stirling Cycle

- 2-3: both pistons move to the right at same rate, keeping const. volume, until the entire gas pushed to the right chamber (passing through the regenerator). Heat is transferred to the regenerator and gas temperature drops to $T_L$.

if we go to the stage 2 or station 2 both the piston moves to the right at the same rate.

**(Video Starts: 24:44)**

Here you can see are moving the same rate.

**(Video Ends: 24:47)**

Keeping constant volume until the entire gas pushes to the right chamber passes through the regenerator. Heat is transferred to the regenerator and gas temperature drops to T L.

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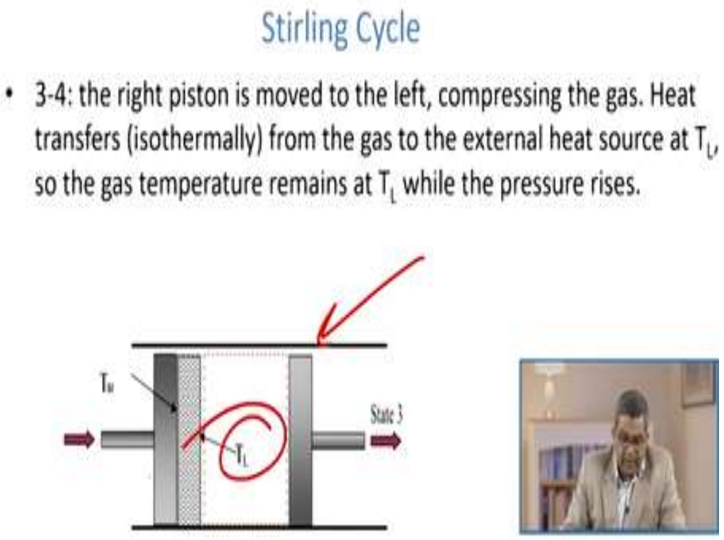

Stirling Cycle

- 3-4: the right piston is moved to the left, compressing the gas. Heat transfers (isothermally) from the gas to the external heat source at $T_L$, so the gas temperature remains at $T_L$ while the pressure rises.

**(Video Starts: 25:14)**

if we go to station 3 to 4 the right piston this one.

**(Video Ends: 25:17)**

The right piston is moved to the left compressing the gas and heat transfer isothermally from gas to external heat source maintained at T L, so the gas temperature remains at T L while the pressure rises.

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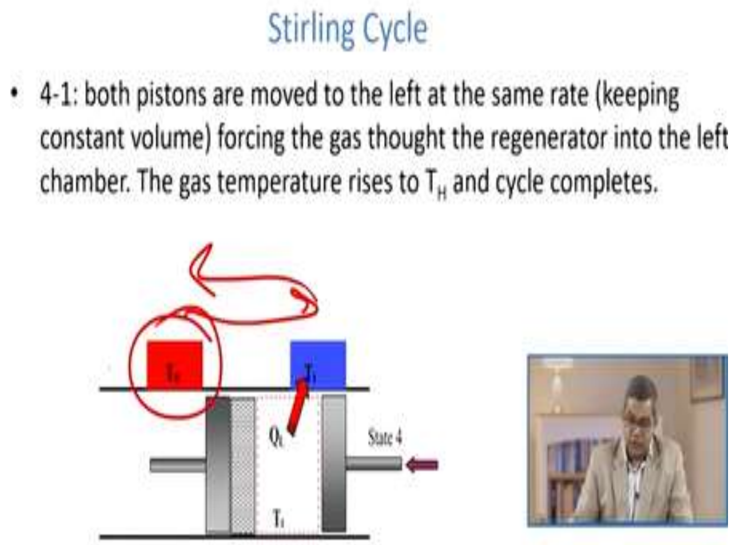

Stirling Cycle

- 4-1: both pistons are moved to the left at the same rate (keeping constant volume) forcing the gas thought the regenerator into the left chamber. The gas temperature rises to $T_H$ and cycle completes.

in the last stage that is from 4 to 1, both the pistons are moved to the left at the same rate, keeping constant volume and forcing the gas through the regenerator into the left chamber. the gas temperature again rises to T H and cycle completes.

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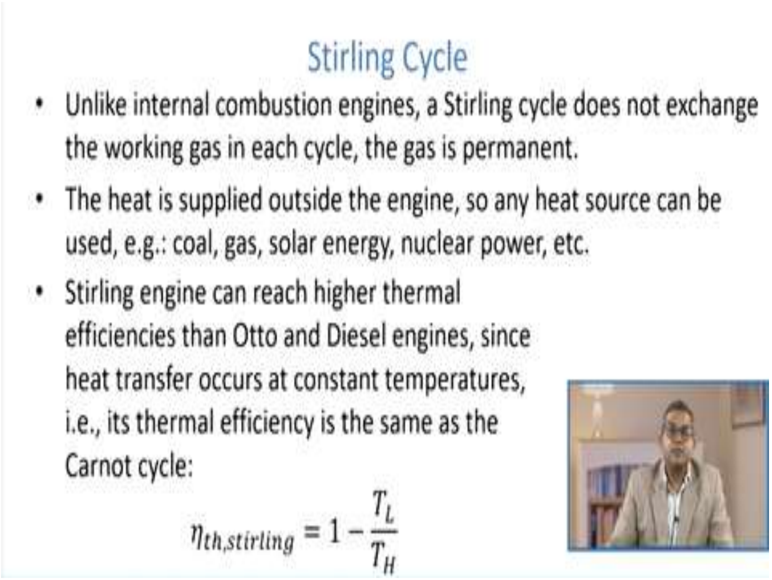

Stirling Cycle

- Unlike internal combustion engines, a Stirling cycle does not exchange the working gas in each cycle, the gas is permanent.
- The heat is supplied outside the engine, so any heat source can be used, e.g.: coal, gas, solar energy, nuclear power, etc.
- Stirling engine can reach higher thermal efficiencies than Otto and Diesel engines, since heat transfer occurs at constant temperatures, i.e., its thermal efficiency is the same as the Carnot cycle:

$$\eta_{th,stirling} = 1 - \frac{T_L}{T_H}$$

So, unlike an internal combustion engine, a stirling cycle does not exchange the working gas in each cycle and the gas is permanent. The heat is supplied outside the engine to use any heat source, maybe coal gas, solar energy, nuclear power, etcetera. A Stirling engine can reach higher thermal efficiencies than an otto or a diesel engine since the heat transfer occurs at constant temperature that is its thermal efficiency is the same as per the Carnot cycle.

So, if we try to calculate the efficiency of the eastern Stirling cycle that is

$$\eta_{th,\,stirling} = 1 - \frac{T_L}{T_H}$$

The pressure changes are very smooth, and its torque is uniform so it has no wall exhaust pipe etcetera. Thus, Stirling cycle is quite and has less maintenance point. So, in other words it is quite economical. To achieve competitive efficiency, it needs to work on high pressures that cause the tremendous sealing problem.

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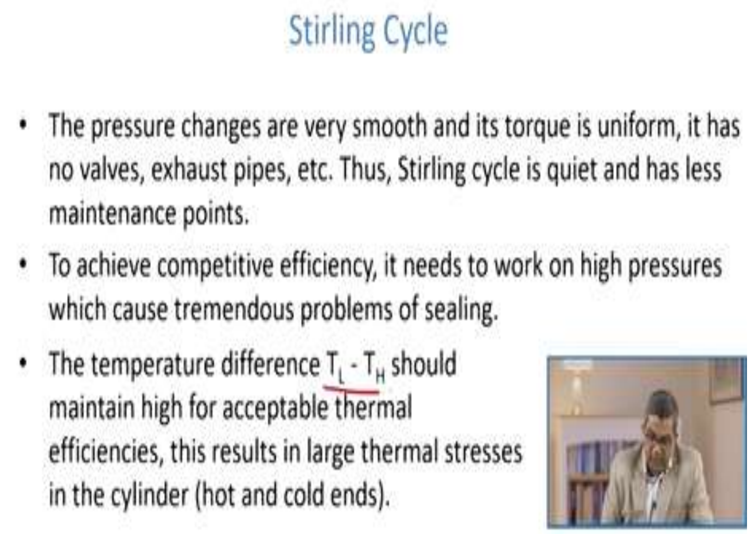

## Stirling Cycle

- The pressure changes are very smooth and its torque is uniform, it has no valves, exhaust pipes, etc. Thus, Stirling cycle is quiet and has less maintenance points.
- To achieve competitive efficiency, it needs to work on high pressures which cause tremendous problems of sealing.
- The temperature difference $T_L - T_H$ should maintain high for acceptable thermal efficiencies, this results in large thermal stresses in the cylinder (hot and cold ends).

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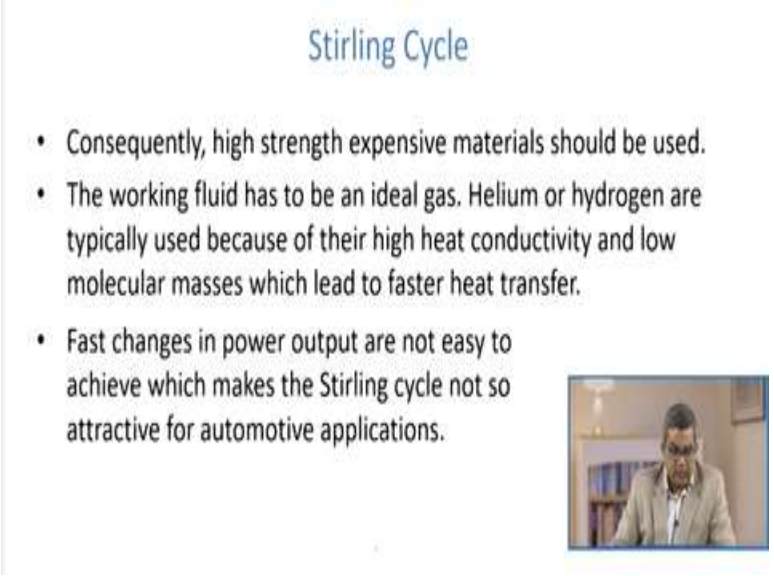

## Stirling Cycle

- Consequently, high strength expensive materials should be used.
- The working fluid has to be an ideal gas. Helium or hydrogen are typically used because of their high heat conductivity and low molecular masses which lead to faster heat transfer.
- Fast changes in power output are not easy to achieve which makes the Stirling cycle not so attractive for automotive applications.

Consequently, high-strength expensive material should be used. The working fluid has to be an ideal gas; maybe Helium or Hydrogen are typically used because of their high heat conductivity and low molecular masses, which lead to faster heat transfer. Fast changes in power output are not easy to achieve, making the sterling cycle not so attractive for automotive applications.

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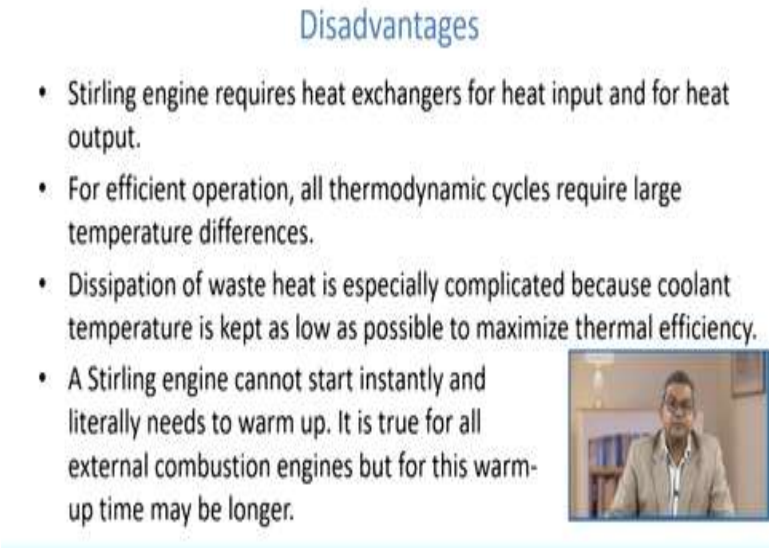

## Disadvantages

- Stirling engine requires heat exchangers for heat input and for heat output.
- For efficient operation, all thermodynamic cycles require large temperature differences.
- Dissipation of waste heat is especially complicated because coolant temperature is kept as low as possible to maximize thermal efficiency.
- A Stirling engine cannot start instantly and literally needs to warm up. It is true for all external combustion engines but for this warm-up time may be longer.

There are so many disadvantages associated with the Stirling engine. One is that the Stirling engine requires heat exchangers for heat input and heat output. For efficient operation, all thermodynamic cycles require large temperature differences. Dissipation of waste heat is especially complicated because coolant temperature is kept as low as possible to maximize thermal efficiency.

A Stirling engine cannot start instantly and literally needs to warm up. Because of this some latent time is needed. It is true for all external combustion engines, but it may be a bit longer for this warm-up time. So, at the outset in this particular lecture, we had a discussion about the various heat transfer fluids and as well as we discussed the basic concept of the Stirling cycle which is quite useful in various CSPs.

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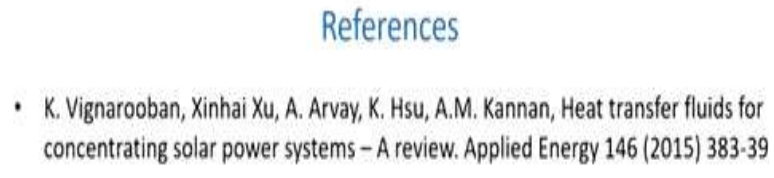

## References

- K. Vignarooban, Xinhai Xu, A. Arvay, K. Hsu, A.M. Kannan, Heat transfer fluids for concentrating solar power systems – A review. Applied Energy 146 (2015) 383-39

And if you wish to have further study you can have a look about this particular reference. Thank you very much.